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THE MODIFIED BARROWMAN METHOD WITH APPLICATIONS TO THE OPDAMS AND PDAMS VEHICLES

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The Barrowman Method is an accurate, low-cost algorithm for the calculation of aerodynamic parameters of rockets. The method has been modified to allow the use of airfoiled wings and fins with control surfaces and to include the effects of downwash from the wings on the fins. It has been shown that interdigitation of the wings and fins significantly reduces the downwash. The Modified Barrowman Method has been applied to PDAMS and compared to wind tunnel results. An aerodynamic model of the OPDAMS vehicle was generated.

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I. INTRODUCTION

The Barrowman Method [1] provides an excellent, low-cost, tool for the evaluation of the aerodynamic model of a rocket. The primary limitation is its restriction to noncontrollable sheet fins. This report presents the basic Barrowman Method which pertains to the body of the rocket. Also presented are modifications to the basic method, which allows for the incorporation of airfoil-shaped fins with control surfaces and wing/fin combinations.

The resulting Modified Barrowman Method (MBM) was applied to the aft-wing configuration of PDAMS. This was done so that a comparison of MBM results and wind tunnel data could be made. A second comparison was made with MBM results and the current PDAMS aeromodel. The comparisons are presented herein for evaluation of the method.

An aerodynamic model of the OPDAMS vehicle has been generated through the use of the MBM.

II. THE MODIFIED BARROWMAN METHOD

The Barrowman Method is a means of calculating the aerodynamic characteristics of a rocket. The method is based on USAF DATCOM, with simplifications of fixed sheet fins. The method is based on normal force coefficients and is only valid in the linear regime. The modifications to the method allow for the use of published data for airfoiled fins with control surfaces and wing/fin combinations. The results of interdigitation of the wings and fins in a cruciform configuration is demonstrated.

A. The Barrowman Method

The first element of the Barrowman Method is that the normal force contribution of a straight, constant diameter body tube is zero. Only the nose, body diameter transition sections, and fins contribute to the normal force of the rocket. Calculations are performed with the normal force coefficients. All centers of pressure (CP) are referenced to datum zero (0), which is located at the nose.

The centers of pressure of nose cones and body transition sections are located by dividing the volume of the component by the area at the component's highest datum. This gives the center of pressure location from the component's base. A transform is required to calculate the datum of the CP.

All nose cones have the same normal force coefficient values, providing the base area is the reference area. Equation (1) gives the normal force coefficient for nose cones.

$$(C_{n_\alpha})_n = 2.0 \qquad (1)$$

Convention will be set such that the area of the base of the nose is the reference area. Otherwise, a scaling factor equal to the nose base area divided by the reference area is required to multiply $(C_{n_\alpha})_n$.

The normal force coefficients of body transition sections are calculated by Equation (2),

$$(C_{n_\alpha})_T = 2.0 \left[\left(\frac{r_2}{r_{ref}}\right)^2 - \left(\frac{r_1}{r_{ref}}\right)^2\right], \tag{2}$$

where r_1 is the radius of the body at the end of the transition section with the lower datum, and r_2 is the body radius at the higher datum of the transition section. The reference area, S_{ref}, is equal to the area of a circle with radius r_{ref}. It can be seen that an expansion section yields a positive $(C_{n_\alpha})_T$, while a contracting section provides a negative $(C_{n_\alpha})_T$.

For a continued description of the Barrowman Method, it will be assumed that the normal force coefficient and the longitudinal and radial locations of the center of pressure of the fins are known. The means of calculating these parameters will be presented in modifications to the Barrowman Method.

The total normal force coefficient of the rocket is obtained by summation of all of the constitutant normal force coefficients

$$C_{n_\alpha} = \sum_i (C_{n_\alpha})_i. \tag{3}$$

The location of the overall center of pressure of the vehicle, $\overline{Z}$, is given by Equation (4).

$$\overline{Z} = \left(\sum_i (C_{n_\alpha})_i Z_i)/(\sum_i (C_{n_\alpha})_i\right) \tag{4}$$

The datum of the center of pressure of the normal force contributing components are the Z_i.

With the preceeding data the moment coefficients can be calculated. The reference length is the body diameter in the reference section, $D = 2r_{ref}$. The C_{m_2} coefficient is given by Equation (5).

$$C_{m_\alpha} = C_{n_\alpha}\left(\frac{\overline{Z}-\overline{W}}{D}\right) = C_{n_\alpha}\,(SM) \tag{5}$$

$$(SM) = (\overline{Z}-\overline{W})/D \tag{6}$$

The vehicle's center of gravity is given by $\overline{W}$. The static margin is denoted by (SM). Thus, for a stable rocket design the static margin must be greater than zero, or in other words, $\overline{Z}>\overline{W}$.

The damping moment coefficient, $C_{m_{\dot\alpha}}$, is given by Equation (7).

$$C_{m_{\dot\alpha}} = \sum_i (C_{n_\alpha})_i \; (Z_i-\overline{W})^2/D^2 \tag{7}$$

Since the nose and body transition sections exhibit radial symmetry, they do not contribute to the roll moments. Thus the fins are the only contributor to the rolling moments. The radial location of the CP of the fins, Y_F, is found by calculation of the radial centroid of the exposed fin area. It is assumed that the vehicle's center of gravity lies on the vehicle's centerline. The calculation of the C_{LP}, the rolling moment coefficient due to a roll rate, P, is calculated by Equation (7), where Y_i is substituted for Z_i and $\overline{W}$ is the radial location of the center of gravity, multiplied by the number of wing pairs (two, for cruciform wings).

The constants are used in Equation (8-10), which are the homogeneous equations of motion for a non-thrusting rocket.

$$I_L \ddot{\alpha} + \frac{\rho}{2} \upsilon S_{ref} D^2 C_{m_{\dot{\alpha}}} \dot{\alpha} + \frac{\rho}{2} \upsilon^2 S_{ref} D C_{m_\alpha} \alpha = 0 \tag{8}$$

$$I_L \ddot{\beta} + \frac{\rho}{2} \upsilon S_{ref} D^2 C_{m_{\dot{\beta}}} \dot{\beta} + \frac{\rho}{2} \upsilon^2 S_{ref} D C_{m_\beta} \beta = 0 \tag{9}$$

$$I_R \dot{P} + \frac{\rho}{2} \upsilon S_{ref} D^2 C_{LP} P = 0 \tag{10}$$

Due to the symmetry of the rocket, the α-derivatives and β-derivatives are equal.

For vehicles that are propelled by rockets, the exhaust jet of the engine provides a damping term that needs to be included in Equation (8)(9).

The $C_{m_{\dot{\alpha}}}^{exh}$ is given by Equation (11) and its use is shown in Equation (12). For completeness of the method, similar augmentation of the β equation is required.

$$C_{m_\alpha}^{exh} = \dot{m}(L_{n_e} - \overline{w})^2/D^2 \tag{11}$$

$$I_L \ddot{\alpha} + \frac{\rho}{2} \upsilon S_{ref} D^2 C_{m_{\dot{\alpha}}} \dot{\alpha} + D^2 C_{m_{\dot{\alpha}}}^{exh} \dot{\alpha} + \frac{\rho}{2} \upsilon^2 S_{ref} D C_{m_\alpha} \alpha = 0 \tag{12}$$

Where m is the mass flow rate of the rocket engine and L_{ne} is the datum of the rocket nozzle's exhaust plane. At engine burnout, m becomes zero and Equation (12) becomes Equation (8).

B. Modifications of the Barrowman Method for the Use of Airfoiled Fins with Control Surfaces and Airfoiled Wings

The techniques developed for the modifications to the Barrowman Method have been generalized and can be applied to a wide variety of configurations and airfoils.

To start, obtain the two-dimensional airfoil data from a source such as Hoerner [2] or Riegels [3]. Since rockets generally use symmetric airfoils for fins, $C_{\ell_o} = 0$ and $C_{m_o} = 0$. For a non-symmetric airfoil the non-zero C_{ℓ_o} and C_{m_o} terms can be added to the following C_ℓ and C_m terms. The transformation of the infinite span lift coefficient, $(C_{\ell_\alpha})_o$, to a finite span, C_{ℓ_α}, is given by Equation (13).

$$(C_{\ell_\alpha})_w = [1 + (C_{\ell_\alpha})_o/\pi \mathcal{R} \varepsilon]^{-1} (C_{\ell_\alpha})_o \tag{13}$$

Where $\varepsilon = 0.95$ for elliptic wing loading. The lift coefficient is now area scaled to the reference area of the rocket. Considering a wing with constant chord, $\bar{c}$, and span, S, the wing area, A_w, is the product of the chord and span. The virtual airfoil passing through the rocket's body is required for these calculations. Usually there are some cut-outs in the airfoil for control boxes and such that must be taken into account. This is accomplished by subtracting the cut-out area, A_c, from the wing area A_w. Equation (14) presents the wing lift scaled to the rocket's reference area.

$$C_{\ell_\alpha} = (A_w - Ac)(C_{\ell_\alpha})_w/S_{ref} \tag{14}$$

With the lift acting at the quarter chord, and since these calculations are valid in the linear regime, the small angle approximation can be applied. This suggests that the normal force coefficients are equal to the lift coefficients. At this point, the Barrowman Method calculations for static stability coefficient can be done.

The control surface calculations are also started from a source such as Hoerner or Riegels [2,3]. These sources contain wind tunnel data for various control surfaces on different airfoils. The data indirectly gives $C_{\ell\delta}$ and C_{m_δ}, as the data presented is usually $\partial\alpha/\partial\delta$ and $\partial C_{m_{(c/4)}}/\partial\delta$. For $C_{\ell\delta}$ the chain rule is applied to the result of Equation (14).

$$(C_{\ell_\delta})_{fs} = C_{\ell_\alpha} \frac{\partial\alpha}{\partial\delta} \tag{15}$$

The control surfaces are usually not full-span due to such things as control boxes and not extending to the wing tips. To account for this, an empirical method based on Weissinger's Method [4] is used. The graphs allow for the determination of K_f and K_{f_i}. The factors are calculated from these parameters determined from graphs [4]. The result of K_f or K_{f_i} is dependent on whether the outer or inner span of the control surface is used. If the control surface extends to the wing tips, then $K_f = 1$.

$$K_f(K_{f_i}) = k_1\Big(1 + k_2 \,(\mathcal{R}\sqrt{1-m^2} - 6) + k_3 \,\sin\big(\tan^{-1}(\tan \Lambda_{1/2}/\sqrt{1-m^2})\big)\Big) \tag{16}$$

$$C_{\ell_\delta} = (K_f - K_{f_i})(C_{\ell_\delta})_{fs} \tag{17}$$

For $\delta \neq 0$ there is a moment about the quarter chord. Equation (18) is a means of calculating the torque couple about the wing's quarter chord.

$$C_{m_{(c/4)\delta}} = (K_f - K_{f_i}) \cdot \frac{\bar{c}}{D} \frac{A_w - A_c}{S_{ref}} \frac{\partial C_{m(c/4)}}{\partial \delta} \tag{18}$$

This term is added to the torque term generated by the lift of the control surface.

$$C_{m_\delta} = \frac{(\bar{W} - Z_f)}{D} C_{\ell_\delta} + C_{m(c/4)\delta} \tag{19}$$

This generates a forcing term for Equation (8) as shown in Equation (20).

$$f(\alpha, \frac{d}{dt}) = \frac{\rho}{2} \upsilon^2 S_{ref} D C_{m_{\delta_e}} \delta_e \tag{20}$$

Since C_{m_δ} and $C_{m_{(c/4)\delta}}$ are both negative, this implies that $\delta_e(r)$ positive produces a negative pitching (yaw) moment. A sign change may be performed at C_{m_δ} to agree with the convention used.

The roll derivative $C_{L_{\delta a}}$ is calculated from C_{ℓ_δ} and the radial centroid of the control surface $(Y_F)_{cs}$. Since each control surface is independent of the other, the aileron control surface angle (δ_a) is obtained from unequal elevator or rudder flap pair deflections.

$$\delta_e = (\delta_2 + \delta_4)/2 \tag{21}$$

$$\delta_r = (\delta_1 + \delta_3)/2 \tag{22}$$

$$\delta_a = (\delta_2 - \delta_4 + \delta_1 - \delta_3)/2 \tag{23}$$

With the calculation of $C_{L_{\delta_a}}$, the nonhomogeneous roll equation can be written

$$C_{L_{\delta_a}} = (Y_F)_{cs} \, C_{L_{\delta_a}}/D \tag{24}$$

$$g(P, \frac{d}{dt}) = \frac{\rho}{2} \upsilon^2 S_{ref} D C_{L_{\delta_a}} \delta_a \tag{25}$$

This completes the Modified Barrowman Method for a standard rocket configuration such as PDAMS. For the configuration of OPDAMS, (basically a PDAMS with forward wings) the effects of the wings on the fins need to be known. The primary effect is downwash induced by the wings on the tail.

For wings that are in line with the fins, the calculation of the downwash is straightforward [4]. For interdigitated wing/fins the calculations need to be modified. Due to symmetry, consider the wings to be level with some angle of attack to the airflow. For cruciform wings and fins, the plane of the fins is inclined at $\pi/4$ rad for interdigitation. Thus, projection of the fin areas onto the plane of the wing is given by Equation (26).

$$A_P = 2A_T \cos\frac{\pi}{4} = \sqrt{2}\, A_T \tag{26}$$

The angle of attack generates two components from the rotation of the fins to an interdigitated position. One component is spanwise and the other is in the plane perpendicular to the span. The projection of the airflow onto the plane perpendicular to the flow yields an effective angle of attack for the fins of α_E.

$$\alpha_E = \alpha \cos \pi/4 \tag{27}$$

The lift of the fins becomes Equation (28):

$$\begin{aligned} L &= \frac{1}{2}\rho\ \alpha\ C_{\ell_\alpha}\ \upsilon^2\ A_P\alpha_E \\ &= \frac{1}{2}\rho\upsilon^2\ C_{\ell_\alpha}\ A\alpha \end{aligned} \tag{28}$$

For calculations, Equation (28) proves that cruciform fins interdigitated with cruciform wing by $\pi/4$ rad can be considered to be in line, with one exception - downwash. The downwash, $\frac{\partial\varepsilon}{\partial\alpha}$, is performed in the same manner, but now the aerodynamic center is above the plane of the wings by $\sqrt{2}\ Y_F/2$. This vertical displacement reduces the effect of downwash. The downwash is reduced by 31 percent for the OPDAMS vehicle. Thus, the fins experience a greater angle of attack, which increases lift and eliminates the requirement of larger fins. Therefore, the advantage to interdigitation is significant.

III. PDAMS Aerodynamic Models

Two PDAMS aerodynamic models have been formulated via MBM. The first model corresponds to the aft-wing configuration used by Killough during wind tunnel testing [5]. A comparison of the MBM theoretic model and the wind tunnel data is presented as a demonstration of the technique. An aeromodel of the current PDAMS vehicle was calculated from the elements of the aft-wing configuration. This was compared to the current PDAMS aeromodel. There was good agreement of the MBM model and the wind tunnel data. There were differences with the current aeromodel, with the major difference being in the C_{m_δ} term. The implications of this major difference are discussed.

A. Comparison of the MBM Model with Wind Tunnel Data

The PDAMS aft-wing configuration aerodynamic coefficients were derived from wind tunnel data. The data was presented in tabular form for a range of α and δ. The derivatives were calculated by averaging the slopes of the data in the linear regime, $-0.175 \text{ rad} \leq \alpha \leq 0.175$ rad. This was done to correct a 6 percent asymmetry in the data about $\alpha = 0$. Due to the symmetry of the vehicle, full data for δ was not taken, but rather only for $\delta \leq 0$ rad. Thus, the delta derivatives were calculated for only $\delta \leq 0$. The wind tunnel data is presented by the averages, with the variances, both positive and negative, shown in parentheses.

TABLE 1. Comparison of MBM Model with Wind Tunnel Data

Coefficient	Wind Tunnel Data	MBM Results	Percent Difference
C_{n_α}	$18.96\ {}^{+0.94}_{-1.12}$	19.04	0.4
C_{n_δ}	$8.10\ {}^{+0.63}_{-0.26}$	8.15	0.6
C_{m_α}	$16.92\ {}^{+3.14}_{-2.23}$	19.88	15
C_{m_δ}	$-15.14\ {}^{+3.66}_{-0.44}$	-14.11	7
C_{L_δ}	$8.05\ {}^{+0.51}_{-0.43}$	8.82	9
$\bar{Z}$(in)	$27.65\ {}^{+1.40}_{-0.92}$	28.56	

B. Comparison of the Current PDAMS Aeromodel with MBM Results

The current PDAMS configuration is not the same as the vehicle that was tested in the wind tunnel. Thus, as a second demonstration of MBM, it was applied to the current configuration. Configuration data was obtained from MICOM Drawing RLC-2077. The current aeromodel was obtained from Mr. Sam Stauffer [6] of Rexham Aerospace.

TABLE 2. Comparison of Current PDAMS Aeromodel with MBM

Coefficient	Current Aeromodel	MBM Results
C_{n_α}	18.03	19.04
C_{n_δ}	7.84	8.15
C_{m_α}	9.13	8.57
C_{m_δ}	-11.87	-9.29
$C_{m_{\dot{\alpha}}}$		52.03
$\partial\alpha/\partial\delta$	-1.30	-1.08
Static Margin	0.51	0.45

The normal force coefficients and roll moment coefficients are the same for both the current model and the aft-wing wind tunnel model for MBM. This is in agreement with the results of Killough [5] for the aft-wing and forward-wing wind tunnel configurations. But there is a difference in the normal force coefficients between the current configuration and the wind tunnel model.

The most significant difference with the current PDAMS aeromodel was in C_{m_δ}. To demonstrate the importance of this term, a pull-up maneuver was formulated. This was done by setting $\delta = 0.262$ rad (15°) with the vehicle traveling in the standard sea-level atmosphere with a constant velocity of 150 m/s (approximately 80 percent of terminal velocity.) The initial calculations were performed in a zero gravitational field. The current PDAMS aeromodel has a turning radius of 370 m while the MBM model has a turning radius of 502 m. The quarter turn where the vehicle enters on the downward vertical and the impact is at the bottom of the loop. A gravitation field was superimposed on the loop, stretching it out. The current aeromodel was used to set the entry and impact point. The MBM aeromodel was put through the same maneuver with the same entry point. The result was a miss of the impact point by 168 m.

This quarter loop maneuver is an analytic example to indicate the effects of a reduced C_{m_δ} for a system with a heavy emphasis on the end-game guidance strategy.

IV. OPDAMS Aerodynamic Model

Two changes to the Baseline OPDAMS vehicle were made to accommodate information received during analysis. First, from the PDAMS calculations, it was observed that there was a difference in the span of the fins between PDAMS and OPDAMS Baseline. Since the OPDAMS aft-end is a PDAMS aft-end, in order to eliminate the need to change the fin spans on the aft-end, the standard PDAMS fins were placed on OPDAMS. This also allows use of PDAMS wind tunnel data to finalize the aerodynamic model.

The second change was due to a shift of the CG by 1.05 inches rearward of the design location [7]. This produced a $\partial\alpha/\partial\delta = 6.4$, which is unacceptable. An equation was formulated which locates the CG as a function of the quarter chord of wing datum, Z_w.

$$\overline{W} = 23.369 \text{ in} + 0.1035\, Z_w \tag{29}$$

This was based on a full-up OPDAMS vehicle with aluminum wing ring [8]. The equations of C_{m_α} (4) and C_{m_δ} (19) were written as functions of Z_w. This system of equations were solved simultaneously for $\partial\alpha/\partial\delta = 1.7$. The result was $Z_w = 20.5$, the leading edge of the wings at 19.0. The result of these two changes were designated OPDAMS Baseline Block II.

TABLE 3. OPDAMS Baseline Block II

Length - 51.25 in
Diameter - 6.00 in
Wing Span - 27.00 in
Wing Chord - 6.00 in
Wing Leading Edge - 19.00 datum
Fin Span - 20.00 in
Fin Chord - 9.00 in
Fin Leading Edge - 42.25 datum
Surface - 33.3 percent chord, overhanging nose balanced flap pivoted about flap's quarter chord, each flap set independently.
Airfoils - NACA 0012, cruciform arrangement with constant chord and no sweep, wings and fins interdigitated.
Mass - 60.89 lb
I_r - 725 lb in^2

TABLE 4. OPDAMS Baseline Block II Aerodynamic Model

C_{n_α}	36.234
C_{n_δ}	8.15
$C_{m\alpha}$	15.959
C_{m_δ}	-27.027
$C_{m_{\dot{\alpha}}}$	183.096
C_{LP}	110.482
C_{L_δ}	8.829
$\partial\alpha/\partial\delta$	-1.694
$\overline{W}$	25.491 datum
$\overline{Z}$	28.1337 datum
Static Margin	0.44
I_{long}	133,000 lb in^2
C_{D_o}	1.18 (analytic estimate)

V. CONCLUSIONS

The Modified Barrowman Method has been presented and compared to wind tunnel tests. The agreement of MBM results and wind tunnel data was excellent. The MBM was applied to OPDAMS and the aerodynamic model for OPDAMS Baseline Block II was presented.

While the theoretic results of MBM characterized the wind tunnel results, it must be stressed that they do not replace wind tunnel data. The MBM is an excellent tool for analysis of rocket designs. There are pathologic cases for which any analytic method, including MBM, will fail. It is the wind tunnel, an immense analog computer, which can best indicate the true aerodynamic model.

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